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A History of NBS/NIST Research on Fire Detectors

Early History of Fire Research at NBS

The celebration of NBS/NIST's centennial year has led to many looks back over a century of research activities. The fire research program at NBS began shortly after the agency's founding in 1901 with the initial funded studies focused on fire resistance and flammability properties of materials beginning with the hiring of Simon Ingberg in 1914. In those days the primary objective of fire research was to prevent fires from burning down large sections of cities. A summary of the early work at NBS was prepared by Dan Gross for the third IAFSS Conference in 1991[1].

The earliest studies at NBS of the performance of detectors were conducted in the 1920's and 30's. In the 1950's pioneering work was conducted by McCamy on flame detectors for aircraft engine nacelles[2] in which he published data on both ultraviolet (UV) and infrared (IR) signatures and proposed coupling IR sensors with flame flicker circuits to discriminate hot objects from actual flame.

Operation Breakthrough

In the late 1960's the US Department of Housing and Urban Development instituted a major, innovative housing demonstration project called "Operation Breakthrough[3]." Intended to facilitate the development of novel approaches to design, materials, and construction techniques of use in addressing low income housing issues, the program included not only the submission of concepts but also the actual construction of a home using the proposed techniques. Recognizing that traditional, prescriptive building codes could not deal effectively with these innovative methods and materials NBS developed one of the earliest performance-based code approaches not too dissimilar from those now being promulgated globally.

At the time of Breakthrough, fire alarm systems in homes were rare, and where installed used commercial detectors and panels designed by the rules applied to commercial properties. Here heat detectors were used in most occupiable spaces. In commercial installations smoke detectors were usually only used to protect high value items, so they were rare in home systems. The typical residential system cost as much (in 1968 dollars) as residential sprinkler systems cost today. The (single-station) smoke alarm had been developed in 1965 but sales were low and availability poor for the few models being marketed.

One of NBS's fire protection engineers, Mr. Richard (Dick) Bright, had been impressed with an article published by Canada's National Research Council in 1962. John McGuire and Brian Ruscoe[4] studied 342 residential fire deaths in Ontario from 1956-1960 and judged the life saving potential of a heat detector in every room or a single, smoke detector outside the bedrooms and at the head of the basement stairs (if the home had a basement). Their judgement was that the heat detectors would have reduced the fatalities by 8% and the smoke detectors by 41%.

NBS included in its Breakthrough criteria[5] (essentially the building code applied to the demonstration houses) a requirement for smoke detectors located in accordance with the McGuire and Ruscoe guidelines. Since only one of each of the selected homes were built and none were ever occupied, no fire experience with these detectors was ever gained.

Hurricane Agnes

In 1971 Hurricane Agnes followed a track up the Chesapeake bay destroying many homes in central Pennsylvania and lower New York. HUD mounted a federal disaster relief effort (this was long before FEMA) including the provision of temporary housing for many poor residents of the region. HUD purchased 17,000 mobile homes (later called manufactured homes) and asked NBS to apply some of the lessons of Breakthrough to the purchase specification. NBS included a requirement for a (single-station) smoke detector outside the bedrooms of each unit. The order for 17,000 smoke detectors had to be split among five manufacturers because at the time no single company had the production capacity to fill the order. Today, one manufacturer could do so with two days' production.

The 17,000 homes were delivered to several sites and were used by families until they could rebuild or find alternative accommodations. Most lived in the homes for a year but some were still occupied three years later. The fire safety statistics were surprising. While there were nearly the statistically expected number of fires, there were no fire deaths and few injuries. The smoke detectors were credited with getting occupants out before they became trapped – just as McGuire and Ruscoe surmised.

This was the first, large installation of residential smoke detectors and the results convinced the manufactured housing industry to adopt the first smoke detector "ordinance." In 1975 it became the policy of the Mobile Home Manufacturing Association (the predecessor of today's Manufactured Housing Institute) that one smoke detector located outside the bedrooms be provided in every manufactured home produced by a member company.

Developing Standards

UL 217

The large procurement of smoke detectors for the Agnes homes piqued Dick Bright's curiosity about just how well these devices performed in detecting fires. He modified a spare prototype of the NBS Smoke Chamber (that later became ASTM D662) to generate smoke from a small source and circulate it with a small bar heater. Hanging production smoke detectors in the box he was appalled to see the "power on" light on many disappear in the smoke without a sound from the detector.

Further tests revealed a problem with smoke entry into the outer housing at low convective flow rates. The smoke box test used by Underwriters Laboratories (UL) at the time had two large fans pointed directly at the detector forcing the smoke in – a not so realistic condition. This experience led Bright and his supervisor Irwin Benjamin to conclude that the potential of residential smoke detectors would not be realized unless there were effective product approval standards that assured their proper performance and reliability.

Bright and Benjamin approached UL about participation in a cooperative project under NBS' Industry Research Associate program where UL would assign an employee to work at NBS for a year to develop the basis for such a standard that UL would then promulgate. I was selected by UL for the one-year assignment, beginning in the Fall of 1973.

One of the unique aspects of this project was that it was conducted in close cooperation with the residential smoke detector industry, who themselves were working with an immature technology. Companies provided samples of current product and were very grateful for constructive criticism. Company engineers began to visit with prototypes of models under development that were jointly evaluated and improved. This cooperative environment led to rapid improvements in the performance of detectors that benefitted the public and the industry.

The work that year covered a number of issues identified as problems (or potential problems) that were corrected by the industry and incorporated in the suggested standard that was presented to UL and formed the basis for the first edition of their Safety Standard for Single- and Multiple-Station Smoke Detectors, UL217. These included:

- Identification and quantification of low velocity smoke entry problems into detector housings or sensor assemblies and the associated Variable Velocity and Directionality tests in the new Standard.

- Design of a new smoke box for sensitivity testing with improvements to the flow characteristics and instrumentation that is now used for all smoke detectors.

- Effects of the condensation of moisture on sensor or circuit boards that could cause false alarms or non-operation and the Humidity Plunge test placed in the Standard to address this issue.

- Development of an electrical transients test to improve reliability by reducing the susceptibility of detectors to damage from transients.

- The application of the "full-scale fire tests" to all smoke detectors where they had previously been used only for ionization type.

- Agreement on the policies of minimum one-year battery life, including the battery with the detector at purchase, the use of commonly available batteries, functional testing features, and others.

In the Fall of 1974 I returned to UL and completed the development and adoption of UL217. Dick Bright had been appointed Chair of the National Fire Protection Association (NFPA) Committee on Household Fire Warning Equipment that developed the NFPA 74 Standard on the Installation, Maintenance, and Use of Household Fire Warning equipment. First published in 1967 as a guide for homeowners this document reflected the philosophy of the times that homes should be protected in the same way as commercial businesses – with a heat detector in every room wired to a fire alarm panel and alarm bells. The cost of such a residential fire alarm system for an average home was about $1500 so they were rare.

NFPA 74

Since the installation of residential fire alarm equipment was voluntary (and no one thought that requiring fire safety equipment in homes would ever happen), Bright felt that homeowners should be given the opportunity to choose a minimum system that provided some protection at low cost, like that suggested by McGuire and Ruscoe. The committee proposed a system of four "Levels of Protection" in the 1974 edition of NFPA 74. These were:

- Level 4 was a smoke detector outside the bedrooms and at the head of any basement stairs from MeGuire and Ruscoe.

- Level 3 added heat or smoke detectors in living or family rooms which had the highest statistical likelihood of residential fire initiation.

- Level 2 added heat or smoke detectors in the bedrooms that were next on the list of fire initiation.

- Level 1 was the full system of a heat or smoke detector in every room.

This unique concept was presented to the NFPA Membership for adoption at the May 1974 meeting in Maimi Beach and it was strongly opposed by the fire service (the Fire Marshals and Fire Chiefs). Their concern was that they saw no evidence that anything less than "complete protection" (Level 1) was adequate. They were correct – the levels were solely based on the judgement of the committee and that of McGuire and Ruscoe.

Full-scale tests of Smoke Detector Performance

The Indiana Dunes Tests[6]

While the Levels of Protection concept was adopted at that meeting the concern expressed by the fire service were not taken lightly. Bright proposed that NBS fund a research project to assess the effectiveness of the Levels of Protection and this contract was awarded to IIT Research Institute and UL. The Principle Investigators were Tom Waterman of IITRI, and William Christian and myself from UL.

The idea was to take detectors currently available on the market and install them in actual homes that were to be demolished. Fires involving actual residential contents would be used and instruments would monitor conditions within the homes to judge when unassisted escape out doors (but not jumping out windows) would no longer be practical.

The research involved 76 experiments conducted over two years in three homes scheduled for demolition as part of an expansion of the Indiana Dunes National Lakeshore Park. The data showed that in fact, the optimum performance was obtained with a smoke detector on every floor level of the home, mostly because smoke flow up stairs could be impeded by flows induced by HVAC systems, especially air conditioning. A closed door at the top of the basement stairs could create a dead air space that delayed response. The home was better protected from fires starting in the basement by a smoke detector on the basement ceiling near the stairway.

The report presented results in a unique way, in terms of the escape time (time between detector alarm and reaching one of the tenability limits defined by the study) provided by the detectors. These escape times were used to produce a probability plot of the percent of experiments in which a given amount of escape time was provided. Thus the reader could select a time needed and determine the percent of cases in which that (or more) time was available.

In an independent analysis of the first year results, a fire safety panel advising the governor of Massachusetts on a statewide detector law an arbitrary 3 minute escape time assumption was applied. This resulted in the observation that a smoke detector on every level would provide the required 3 minutes in 89% of the cases and a smoke detector in every room would only increase that to 93%.

Manufactured Homes

In 1978 the US Department of Housing and Urban Development (HUD) commissioned a study similar to the Indiana Dunes Tests to be conducted in a manufactured home[7]. HUD was preparing to promulgate their federal Manufactured Home Construction and Safety Standards (49CFR3280) and this work provided the basis fo the smoke detector requirements therein.

Smoke Detector Regulations

The Indiana Dunes tests had a strong and immediate impact and soon various jurisdictions began to adopt laws requiring the provision of every level smoke detectors in new residential housing. More surprising to many was the adoption by some of regulations requiring the installation of smoke alarms in existing residences. This ran counter to the U.S. tradition of "a man's home is his castle" and most opposition was not to the smoke detectors but to the change in this tradition. Montgomery County Maryland was one of the first to adopt such an ordinance in 1975, effective in 1978. Even more startling later was the immediate impact of the law. As implementation began the residential fire death rate that had been steady for some years around 32 per year began to drop precipitously. After the law was effective fatalities hit zero in compliant homes and stayed there for several years, convincing others to adopt similar laws.

Successes like Montgomery County led to the rapid adoption of mandatory smoke detectors in most state or provincial building codes in the U.S. and Canada. Codes at the city or county level often went further to require the installation of smoke detectors in existing residential properties. Coupled with effective marketing campaigns by major appliance manufacturers such as GE and Gillette, and retailers like Sears, compliance with these regulations was unusually high – typically above 90%. The result was a decline in U.S. fire deaths by 50% between 1975 and 1998 that has been largely attributed to the smoke detector.

Quantifying Escape Time Needs

The "Indiana Dunes Tests" and other similar studies conducted in the 1970's and 80's clearly demonstrated that the occupants of most homes with every level smoke detectors could expect 3-5 minutes of escape time for most fires. However there were several human factors questions such as how effective smoke detectors were at awakening sleeping people and how much time was needed for a family, especially with young children, to escape.

To address these issues NBS awarded a grant to Prof. E. Harris Nober at the University of Massachusetts at Amherst to conduct a study. Prof. Nober had a sleep lab on campus and experience in this field although like most sleep researchers had focused on insomnia as opposed to awakening.

Prof. Nober's work[8] began in the laboratory but soon moved into homes in order to provide more realism and to address the questions of families. They developed a protocol in which they installed a smoke detector in a test home that could be activated with a radio transmitter from the street. Waiting several weeks to avoid biasing the trial the researchers showed up in the middle of the night and activated the alarm. The subjects were instructed to turn on a bedroom light immediately on awakening (this gave a measure of awakening time) and then place a call to the Amherst Fire Department (who were part of the study and provided a time for the call). Then the family all evacuated outside to a pre-arranged meeting place in front of the house. Through these experiments it was determined that the three minutes assumed almost a decade prior was a typical value for families.

Detection for Special Applications

In the early 1980's NBS decided that the residential smoke detector issues had largely been addressed and the technology matured. Product approval standards (UL217) and installation standards (NFPA74) were in place and the combination of regulatory and voluntary installations were at a pace that soon nearly every home would be equipped. Thus NBS decided to apply its limited resources in other areas.

The result was limited studies mostly aimed at improving detector performance in special applications. The applications addressed included health care facilities[9,10] (especially reducing the incidence of nuisance alarms that were affecting system credibility), fire protection for atria[11] (these had become a common architectural feature), and even spacecraft[12]. NASA had begun advanced planning for their 21st

Century projects including Space Station and wanted to explore innovative techniques for fire detection.

Computational Studies

In the 1990's NIST (formerly NBS) pioneered the use of computational experiments to study the performance of, and to develop guidelines for the installation of smoke detectors. In a project funded through a public/private consortium through the (National) Fire Protection Research Foundation NIST researchers evaluated the effects of both geometry and physical barriers, and the interaction with mechanical ventilation systems on smoke and heat detector activation times. While others have used computational techniques to design specific installations, this was the first time anyone performed parametric calculations designed like a series of experiments to provide systematic information on a hypothesis.

The results of the study were revealing; confirming some common practice and indicating that some assumptions may be wrong. The results had a direct and significant effect on the code requirements.[13,14,15,16]

Current and Future Activities

NIST is still involved in detector research. One project involves the development of an apparatus for evaluating the performance of multi-sensor devices. Called the Fire Emulator/Detector Evaluator (or FE/DE), the apparatus shows real promise for international standardization[17].

With links to the Indiana Dunes Tests, NIST is conducting a new evaluation of residential smoke detectors (now commonly referred to as smoke alarms). This work intends to re-examine the installation and siting rules, the efficacy of current sensor technologies, examine nuisance alarm sources, and develop data with which alarm algorithms might be developed for multi-sensor devices.

Finally, NIST is using its experience in computational fire models to develop a "sensor-driven" or "inverse" model[18]. Where traditional fire models start with the heat release rate of the fire and predict the fire's impact on the building this model takes the analog signal from fire sensors and predicts the heat release rate of the fire most likely to be producing those signals. This model holds promise in allowing fire alarm systems to produce real time data of significant use to the fire service in making tactical decisions, as well as evaluating detector signals for consistency with fire chemistry and physics and determining the level of threat to people and property.

Fire detectors and the systems to which they connect play a significant role in the reduction of fire losses. Thus the NIST fire program will continue to conduct research on detection as a means to achieve its goals of reducing the burden of fire.

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